MINERvA Distributed Power Architecture

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September 24, 2009

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1 System Overview

The MINERvA Experiment [1] seeks to measure low energy neutrino interactions both in support of neutrino oscillation experiments and also to study the strong dynamics of the nucleon and nucleus that affect these interactions.

The MINERvA detector consists of many layers of scintillating fibers sandwiched between large steel plates or modules. Occasionally a neutrino will interact with the steel and the resulting particles will generate photons in the fibers. Photomultiplier tubes (PMTs) convert the photons into a small current which is measured by the front end electronics board (FEB). Metal cylinders containing the PMTs and FEBs are attached to support rails (PMT racks) mounted above the steel plates. The partial detector is shown in Figures 1 and 2.

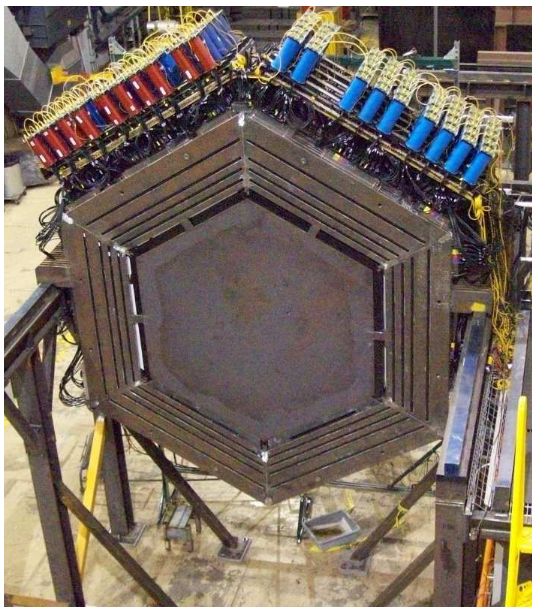

Figure 1: MINERvA detector.

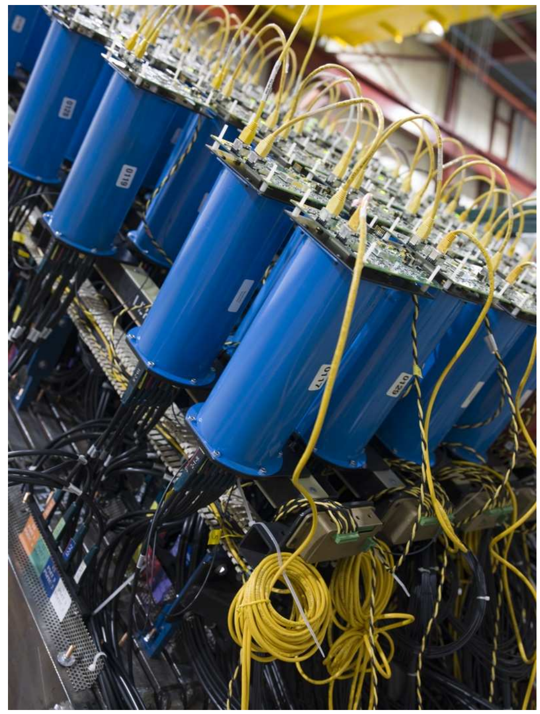

Figure 2: PMT and FEB assembly detail.

The MINERvA data acquisition system (DAQ) is a compact, distributed system consisting of nearly 500 FEBs. A front end electronics chain consists of up to ten FEBs and is connected to a custom VME board (called a CROC) which handles synchronization, configuration and readout. Rather than run low voltage DC power directly to all FEBs a distributed system in employed – bulk 48VDC is distributed to Front End Support Boards (FESBs) which produce the single 4VDC regulated source required to power the FEBs. FESBs are physically located close to the FEBs at the top of the detector to minimize inductance, voltage drop, and EMI emissions. Efficient switching 48VDC power supplies are located in the electronics racks on the platform adjacent to the MINERvA detector. The distributed power architecture is shown below in Figure 3.

Bulk 48VDC is generated by three power supplies which are configured for N+1 redundant operation. Each power supply is hot-swappable so a single unit can be shut down and replaced without any interruption to the system. Since the 48V supplies are capable of producing 120A two levels of fuses are used to limit the current before it is delivered to the FEBs. A fuse

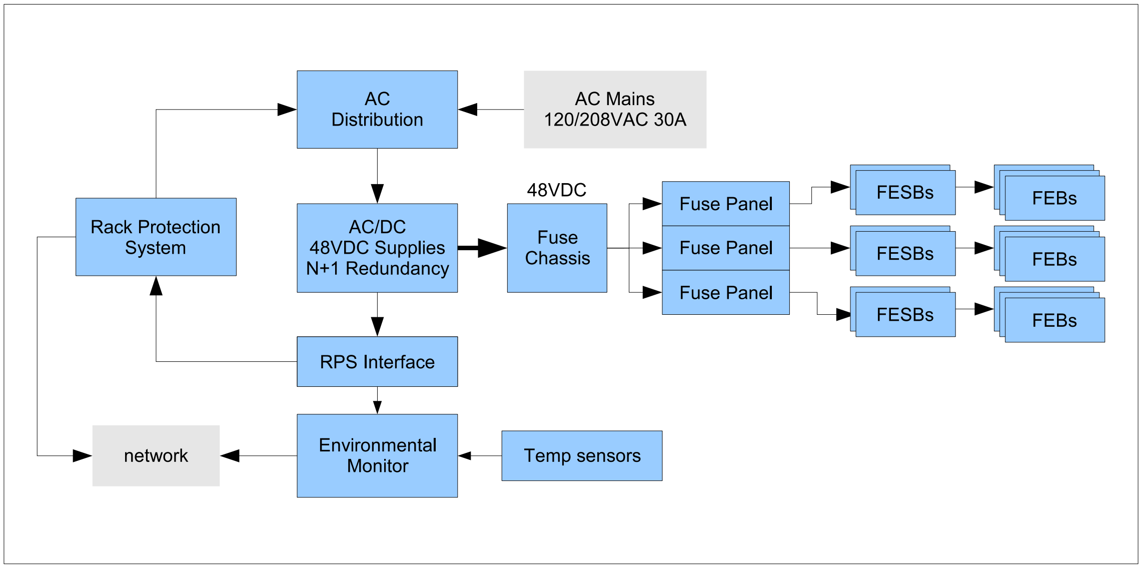

Figure 3: The MINERvA distributed power architecture block diagram.

chassis contains 20A fuses, and each of the fuses feeds a smaller rack mount fuse panel. In the fuse panel each FESB connection is fused at 2A.

The 48VDC is delivered to the FESB which uses an isolated DC-DC converter to produce 4VDC which powers up to ten FEBs (one chain). The FEBs use linear regulators to produce the various voltages needed for the digital and analog circuits.

A rack protection system (RPS) monitors environmental conditions and controls the AC power to the hardware in three electronics racks located on the platform. The 48V supplies interface to the RPS system but provide very basic information such as over temperature and over-voltage warnings. The RPS system also connects to the local network for remote monitoring.

The 48VDC supplies also feature a serial interface through which more detailed information can be obtained. Temperature, current, input and output voltage, hours of operation, and more is available through the power supply serial interface. A small embedded webserver is used to connect the power supplies to the local network.

2 System Components

2.1 48VDC Power Supplies

The telecommunications industry has used 48VDC for decades and as expected there is a large selection of highly reliable power supply equipment available. The AC-DC "Front End" 48V supplies designed for telecommunications often support redundancy, hot-swap, and advanced diagnostics and monitoring. The AC- DC supply we have selected for this application is the FNP1800-48G manufactured by Power-One, Inc. Three FNP1800-48G units plug into the FNR-3 "Power Shelf" 1U chassis as shown in Figure 4.

Each FNP1800-48G supply can deliver up 40A @ 48VDC (1920W). The power budget for all MINERvA FEBs is approximately 3000W, so only two FNP1800-48G units are required. A third FNP1800-48G supply will be installed and used to support N+1 redundant operation. The outputs of the AC-DC supplies are isolated and therefore it is necessary to tie

Figure 4: Three 48VDC power supplies in a 1U rack-mount chassis.

Figure 5: The Rack Protection System.

the 48VRETURN terminal to ground through a resistor. Referencing the supply outputs to ground will prevent common mode voltages from building up and presenting a shock hazard. Remote sensing on the power supply output is not necessary since the input range on the FESB is 36-72VDC.

2.1.1 Environmental and Reliability Specifications

The FNP1800-48G supplies use two high speed brushless fans to provide cooling over a temperature range of $0 - 50\,^{\circ}\mathrm{C}$. The relative humidity must remain in the range of 10-90% and must be non-condensing. The FNP1800-48G data sheet indicates a minimum Mean Time Between Failure (MTBF) of 230,000 hours [2] Fans pull ambient air in from the front of unit and vent out the back into the rack.

2.1.2 Radiated and Conducted EMI

Conducted EMI can occur on the DC outputs and also on the AC inputs. Please refer to the EMC Specifications on page 3 of the FNP1800-48G data sheet for details [3].

2.1.3 External Control and Monitoring

Each power supply has a set of TTL-logic-level outputs for indicating over-temperature, fan status, and DC power OK. These signals are monitored by the RPS unit which generates warning conditions.

Through an $\mathrm{I}^2\mathrm{C}$ serial bus[4] the following parameters may be monitored: output voltage and current, output voltage and current limits, input voltage, temperature, fan speed, hours of operation, serial number, model number, and product revision code, and manufacture location and date. The serial bus also allows the user to enable/disable the output, set the output voltage, set the output current limit, and control the fan speed. The environmental monitor communicates with the power supplies over the serial bus.

2.2 Rack Protection System

The rack protection system (RPS)[5] is responsible for monitoring conditions in three electronics racks on the platform. The 1U rack-mount RPS unit is manufactured by BiRa Systems

Figure 6: AC distribution chassis.

and shown in Figure 5. For MINERvA the RPS unit is configured to monitor the smoke detectors, VME crate power supply voltages, the status of the 48V power supplies and air temperature.

Jumpers are used to configure the RPS unit. The RPS configuration determines which sensors are used and which conditions are to be considered a fault and which conditions are merely warnings. A fault condition will cause the RPS will drop the interlock signal which turns off AC power to all equipment in the racks. Fault and warning conditions are indicated by an alarm and front panel LEDs. Currently smoke detect is the only fault condition.

2.2.1 Remote Access

Remote access to the RPS unit is available over an Ethernet connection. Keep in mind that the RPS status information that is accessible over this interface is very basic and limited to the 24-bit latched status register. Various fault conditions may be reset through the Ethernet interface as well. Refer to the RPS user guide [5] for more information.

The Ethernet interface board used in the RPS unit is a general purpose parallel I/O board `EDAS 1001G-2C5` manufactured by Intelligent Instrumentation [6].

2.3 AC Power Distribution Chassis

A 3U rack mount AC distribution box (Figure 6) is used to house the connectors, wiring, fuses, and circuit breakers needed to connect the power supplies to the three phase 120/208VAC plug (NEMA L21-30, 30A rating). A basic block diagram of the AC distribution system is shown in Figure 7.

Note that one of the single phase (NEMA 5-15) 120VAC outlets is connected to the AC input, bypassing the interlock controlled solid state relay. This outlet is intended to power the RPS chassis, which should always remain “live”. The RPS power outlet is protected by a 2A slow blow fuse (standard 3AG style). All other outlets in the AC distribution chassis are controlled by the interlock input. Schematics, mechanical drawings, and the bill of materials are located in the MINERvA DocDB [7].

2.3.1 Interrupt Capacity

Circuit breakers used in the AC Distribution chassis carry a 2,500 amp interrupt rating. The circuit breakers in the MINOS hall electrical panel meet or exceed Fermilab design guideline of 10,000 amps and therefore no additional protection is required.

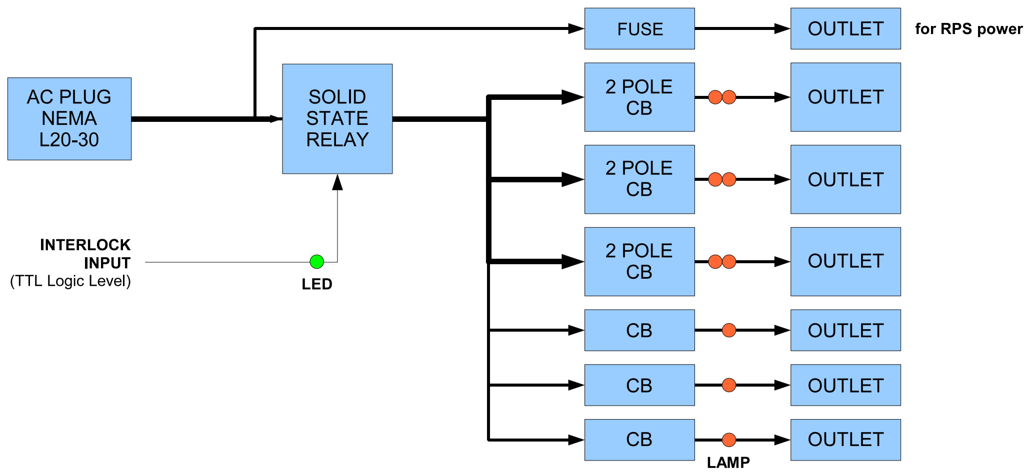

Figure 7: AC distribution chassis block diagram.

2.3.2 Interlock Connection

In order to energize the solid-state relay an external 12VDC “interlock” signal must be connected to the BNC connector on the back of the AC distribution chassis. The BNC connector is center positive and isolated from the chassis. Approximately 10mA is required to keep the solid-state relay energized.

A green LED on the front panel indicates that the interlocks are “made up” and that the AC power may be controlled by operating the circuit breakers. In our configuration the RPS unit drives the interlock signal to three AC distribution units.

2.4 Fuse Chassis

The fuse chassis is a 1U by 16-inch deep rack mount enclosure that is located immediately below the power supply as shown in figure 8. Copper bus bars drop down from the power supply output terminals through a hole cut into the top of the fuse chassis. A clear Lexan shield protects the copper bus bars. Six 20A fuses attach to each bus bar and the outputs are attached to the rear panel.

All twelve 48VDC supply and return connections are fused at 20A and will use 10 AWG wire. Note that the 48VDC return bus is tied to chassis ground through a 1k ohm resistor in the chassis box. This resistor prevents dangerous common mode voltages on the isolated power supply outputs.

2.5 Fuse Panel

Every connection between the power supply and the FESB will be protected by a 2A fuse on the positive 48V wire. GMT fuses are housed in 1U panels [8] as shown in Figure 9. These fuse panels feature two independent buses rated for up to 60A and each bus may have up to ten GMT fuse connections. Logic in the panel can detect a blown fuse and indicates this fault with an LED and contact closure outputs. Three GMT fuse panels will be used.

The fuse panel uses set screw single piece terminal blocks which are not ideal and provide little or no strain relief for wires. In order to properly support the 18AWG FESB power cables

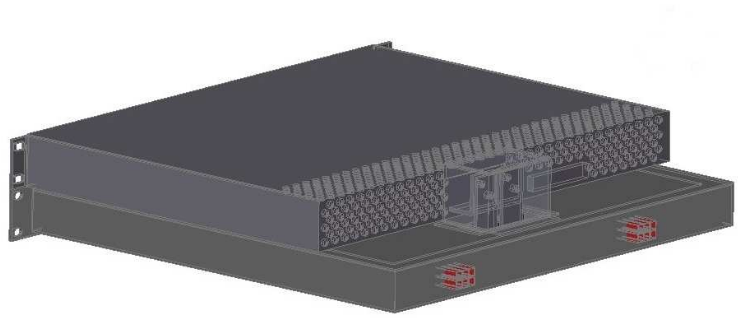

Figure 8: Power supply (top) and Fuse Chassis (bottom), rear view.

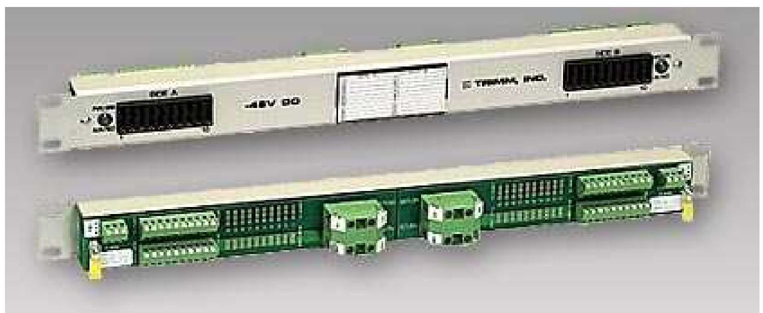

Figure 9: The 1U rack-mount fuse panel.

an enclosure has been designed which attaches to the back the fuse plane and provides 20 robust quick disconnect two-piece connectors.

2.5.1 Replacing Fuses

Blown fuses will be identified by an orange flag that pops up. It is important to note that GMT style fuses can be very fragile and are easily damaged during installation. Be sure to power down the all 48VDC power supplies prior to removing a fuse, and use the fuse extractor tool (looks like large white plastic tweezers) to firmly grasp the bad fuse and gently remove it.

2.6 Front End Support Board

Bulk 48VDC power will be converted to 4VDC using an isolated DC-DC converters attached to the PMT rack. The converter is the SQE48T20050 device manufactured by Power-One.

The DC-DC converter is rated for 5V @ 20A (100W) and measures approximately 25mm x 60mm. Each DC-DC converter will power up to 10 FEBs (one chain), or about 15A @ 4V (60W). The nominal 5V output will be trimmed down to 4.0VDC. The anticipated output current is 15A which is where the converter efficiency peaks at around 92%. The DC-DC converter is equipped with over- voltage, over-current, and over-temperature protection and is designed for high reliability (MTBF = 13.2 million hours). No remote monitoring is used for the FESB and it will be hard wired to turn on when the input voltage reaches 36VDC.

The DC-DC converter, connectors, fuses and filter components are soldered to a small circuit board. Cable connections back to the 48V supply and to the FEBs will connect with

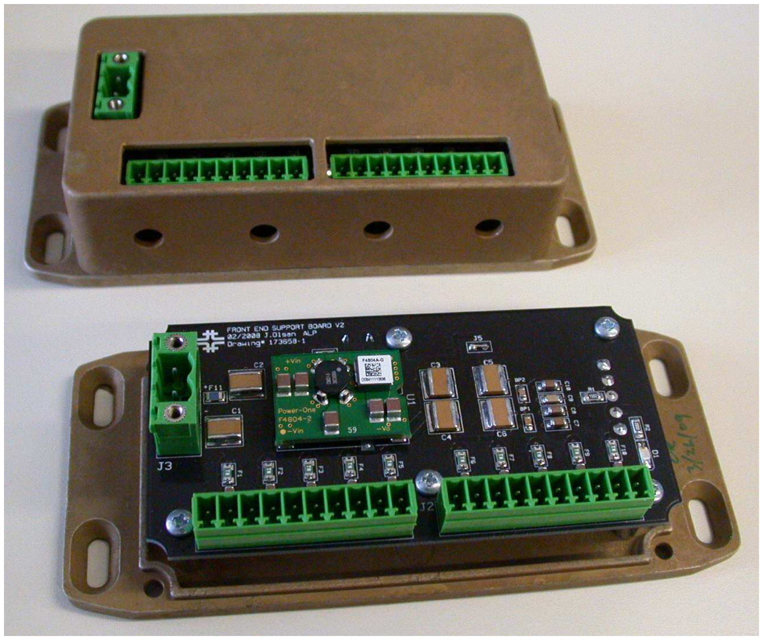

Figure 10: Front end support board (FESB).

two piece terminal blocks. The FESB circuit board will be enclosed in a die cast aluminum box (Figure 10) which will be bolted to the PMT racks above the detector modules. The die-cast aluminum enclosure has been treated (Alodine or equivalent) to resist aluminum oxide and remain electrically conductive.

2.6.1 EMI Considerations

This DC-DC converter is a switch mode device with a nominal switching frequency of 460kHz. When DC-DC converters are used near with highly sensitive analog front end electronics there is always a concern that switching noise will be cause interference. The SQE48T20050 converter already contains an input differential LC filter to attenuate conducted EMI.

Additional noise attenuation (35dB) is realized by using an external input filter module [16]. The DC-DC converter outputs will be filtered using a combination of electrolytic and multi-layer ceramic capacitors per Power-One guidelines [11] A grounded shield plane will be used on the PCB directly under the DC-DC converter as recommended by the manufacturer.

2.7 RPS Interface Board

The RPS Interface board [15]attaches to the back panel of the DC power supply chassis and connects the 48VDc power supply chassis to the RPS and environmental monitor.

The RPS monitors the power supply status bits for fault conditions. If there is an over-temperature, fan failure, or DC output fault the RPS unit will generate warnings. Errors and warning conditions in the RPS may be monitored (and cleared) remotely through the RPS Ethernet interface.

In addition to the basic status bits the power supply serial bus (I^2C) provides a wealth of detailed status information (for example: output current, input and output voltage, temperature, fan speed, serial numbers, and hours of operation counters) and allows for control of

Figure 11: Environmental monitor chassis.

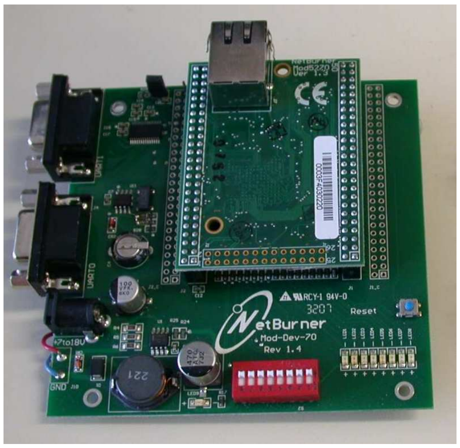

Figure 12: Netburner single board computer.

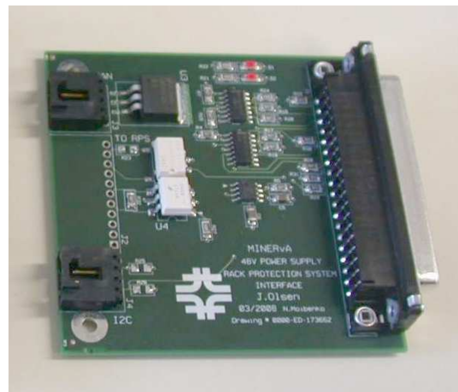

Figure 13: RPS interface board.

individual power supplies. Decoding the serial bus is too complex for the RPS unit so small embedded processor board is used.

2.8 Environmental Monitor

The environmental monitor is a 2U rack-mount chassis that reads temperature sensors at various locations around the detector. In addition to temperature sensors the environmental monitor communicates with the 48VDC power supplies.

Temperature and power supply data are displayed on web pages which are accessed through the Ethernet port. Control of individual 48VDC power supplies is also implemented through the web interface, however a password is required to control the power supplies.

The heart of the environmental monitor is a "Netburner" single board computer (model MOD5270) that is based around a 147MHz 32-bit Freescale Coldfire processor. Applications are written in C and stored in the on board flash memory. At power up the processor loads a minimal real-time OS (RTOS) and loads the web server application and TCP/IP stack. After initialization the processor begins its main scan loop, periodically reading the temperature sensors and 48VDC power supply status data.

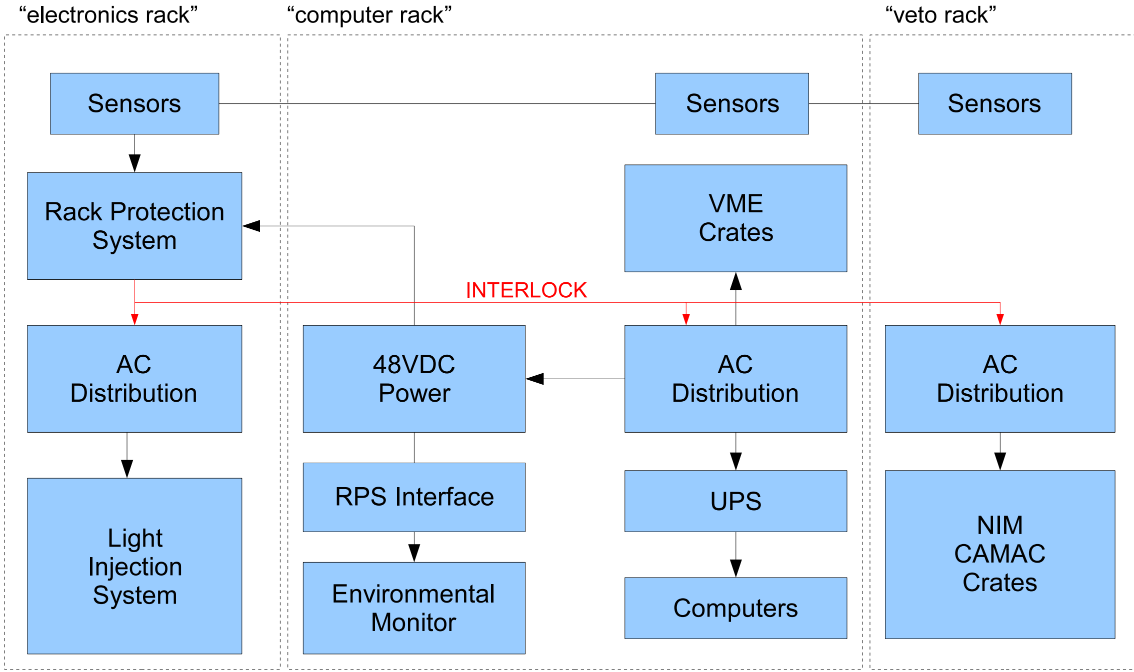

Figure 14: Hardware and rack locations on the platform.

3 Location of Hardware

The MINERvA DAQ system, light injection system, and computers reside in three racks located on the platform adjacent to the detector. Rack locations and components are shown in Figure 14.

4 AC Power Distribution

The AC power arrives on the MINERvA platform from the large circuit breaker panels located on the wall of the MINOS hall. Three 3-phase 208/30A circuits (NEMA L21-30 outlets) are mounted on the platform adjacent to the detector.

An AC distribution chassis is present in each rack. The RPS unit drives an interlock signal that is common to all three racks. If the RPS unit detects smoke in any rack it will drop the interlock, thus shutting off the AC power to all three racks (the RPS unit will remain powered). Note that the PCs and VME crates are running on a UPS, which will continue to supply power for a few minutes while the machines shut down.

5 DC Power Distribution

All conductors meet or exceed Fermilab design guidelines for current carrying capacity [10]. The block diagram of the DC distribution system is shown in Figure 15.

5.1 48VDC Power Supplies to Fuse Chassis

The outputs of the 48VDC power supplies are rated for 48VDC at up to 120A. Large copper bus bars (minimum cross sectional area of 0.125") are used to connect to the Fuse Chassis.

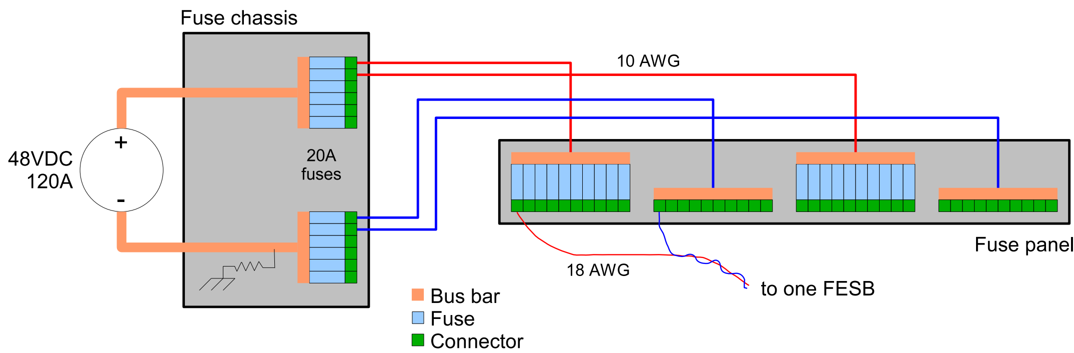

Figure 15: DC power distribution.

Inside the fuse chassis the supply and return buses split into six buses, each fused at 20A and connected with 12AWG wire. Each 20A circuit in the fuse chassis terminates at the back panel with a PowerPole connector (series 1330, rated for 30A) [13].

5.2 Fuse Chassis to Fuse Panel

Each connection from the Fuse Chassis to the Fuse Panel is fused at 20A. For these connections 10AWG stranded THHN wire is used [14]. The insulation used on this wire is PVC with polyamide outer jacket and it meets or exceeds UL VW-1 vertical flame tests. Fuse panels are divided into two sections, each with a supply and return bus. Each fuse panel bus is rated for a maximum of 60A.

5.3 Fuse Panel to FESB

The long cable runs from the Fuse Panels to the FESBs use PVC-jacketed, plenum rated, 18AWG twisted pair cables, Belden part number 9409 [12]. These cables meet or exceed UL VW-1 vertical flame tests and pass Fermilab ES&H internal flame tests. Each supply conductor in these cables is fused at 2A in the fuse panel.

5.4 FESB to FEB

All FESB outputs are fused at 2A and this fuse is not user replaceable. The same Belden cable [12] is used for the low voltage power distribution from the FESB to the FEB. All cabling outside of the racks is secured in wire mesh cable trays.

5.5 Grounding Scheme

The outputs of the DC-DC converter are isolated and the negative output terminal is tied to earth ground at the FESB as shown in Figure 16. A solid mechanical connection will insure that good electrical and thermal contact between the FESB and PMT rack metal. The FESBs are grounded through a wide tin-plated copper braid conductor which is fastened to the main electrical conduit near the lower platform.

The analog and digital “ground” planes on the FEB are not directly connected to earth ground through the mounting hardware. The only other electrical connection to the FEB is

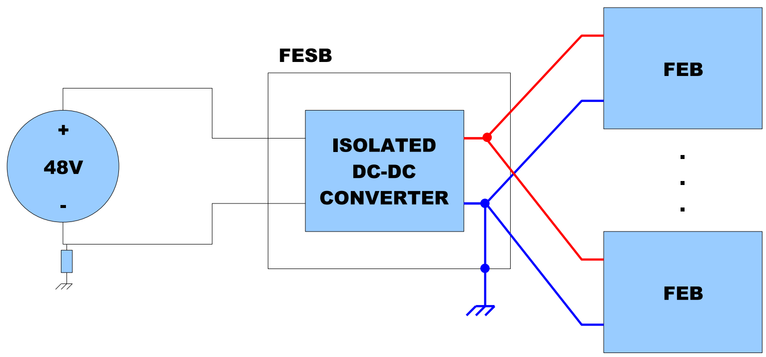

Figure 16: System grounding.

through a cable back to the CROC. (While this cable does in fact include a “signal ground” conductor the FEB connects to it through a 100 ohm resistor thus avoiding ground loops.)

6 Thermal Considerations

6.1 48VDC Power Supplies

When operating at full load the power supplies will be delivering approximately 3000 Watts. Assuming 90% efficiency this will result in 300W added to the rack. Airflow in the power supplies is front to back. A fan pack has been placed in the rear of the rack behind the power supply shelf and helps to push the hot air upwards and out the top of the rack. A perforated metal grill or screen has been installed on the top of each rack.

6.1.1 Maintenance Recommendations

Periodic removal and cleaning of the 48VDC power supplies is recommended as the MINOS hall can be quite dusty. Since the power supplies are configured as an N+1 redundant array it is possible to remove, clean, and reinstall a supply one at a time without interrupting DAQ operations.

6.2 FESB

Passive cooling will be employed to dissipate the heat (approximately 5W) generated in the FESB enclosure. The top and bottom sides of the FESB feature ventilation holes to encourage natural convection. Natural airflow is however not effective at removing the heat from the DC-DC converter. The DC-DC converter is cooled by inserting a thick conformal heat sink foam pad (“gap filler”) between the DC-DC converter and the FESB aluminum base plate. Thermal grease between the FESB enclosure and the detector steel provides a low thermal impedance path for drawing heat away from the FESB. Testing has shown these passive cooling techniques to be quite effective and the maximum converter temperature measured was approximately 40 °C.

A thin thermal pad material will be used between the FESB and the PMT rack metal components, effectively creating a large heat sink.

7 Remote Control and Monitoring

Both the environmental monitor and RPS unit connect to the local Ethernet network and support remote control and monitoring. The RPS unit supports only the basics – fault and warning conditions are reported and may be cleared remotely. The environmental monitor features a webserver and displays detailed power supply status information as well as readings from several temperature sensors.

7.1 RPS Power Supply Warnings

Each power supply generates a few status bits (over-temperature/fan-failure, and DC output OK) which are monitored by the RPS unit. The status bits from the three power supplies are combined with basic AND/OR logic on the RPS interface board and sent to the RPS unit, which is configured to generate warnings based on these status bits. Unfortunately the RPS unit has no general purpose input that can be used for the power supply status bits. Since water cooling is not used in MINERvA racks the "water sensor" inputs on the RPS have been redefined and are used to monitor the 48VDC power supplies. It is important to note the following:

- If any 48VDC power supply detects that the DC output voltage is out of specification it will result in a water temperature warning.
- If any 48VDC power supply detects an over-temperature or fan failure (or even a slow fan) condition it will generate a water flow warning.
- A water flow warning or water temperature warning will not interrupt the AC power to the supplies.
- If a power supply is on AC power but the outputs have been disabled both water flow and water temperature warnings will be generated.

7.2 Network Connection and Security

Neither the RPS unit nor the environmental monitor support DHCP so an IP address must be assigned to each device. Access to both devices should be restricted to shifters and experts only as the controls can completely shut down the DAQ system. A mananged router with a hardware firewall is recommended to restrict access to the RPS and environmental monitor. The environmental monitor webserver is very basic and does not support any sort of authentication or encryption protocols such as SSH or HTTPS.

8 Production Testing

All FESB modules are tested on the bench under full load for a minimum of 8 hours. Each FESB output is checked to insure that the output voltage is between 3.8 and 4.0VDC under full load (1.5A) conditions. FESBs that have passed "burn in" testing are marked with a date on the base plate flange.

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